SECTION 1

INTRODUCTION

Control of combined and storm sewer runoff is a problem of increasing importance in the field of water quality management. The control of combined sewer overflows employing structural measures such as sewer separation, storage and treatment have been used for a number of major cities in the United States. Nationwide application of these techniques for the control of combined sewer overflows would require expenditures critically taxing present and forseeable future resource allocations. New strategies are needed to reduce these costs to tolerable limits. Non-structural controls such as sewer system upgrading and active maintenance, improved catchbasin operation, street sweeping and sewer flushing are upstream collection system management practices that collectively can reduce total combined sewer pollutant loadings and accordingly the costs of downstream structural controls.

The concept of depositing solids control in sewer lines, although widely used around the turn of the century as a maintenance practice, is still in its infancy in regard to being viewed as a viable pollution control alternative for combined sewer systems. Much theoretical but little applied research has been performed to develop and quantify uniform criteria for estimating deposition loadings and for flushing sewers.

The deposition of sewage solids during dry weather in combined sewer systems has long been recognized as a major contributor to "first-flush" phenomena occurring during wet weather runoff periods. The magnitude of these loadings during runoff periods has been estimated to range up to 30 percent of the total daily dry weather sewage loadings. Estimation of these loadings for a given sewer system is an extremely difficult task. Measurement for extended periods is possible but extremely expensive. Some literature information is available from experiments on build-up of sanitary sewage solids in a pilot sewer study conducted by the FMC Corporation (1). No predictive procedures are available for estimating deposition build-up as a function of collection system characteristics. These predictive procedures are necessary as a first step in the development of sewer flushing programs as a non-structural management practice.

1.1 Purpose of Study

The purpose of this study is to provide municipal managers and planners with technical information on the amount and location of pollutant deposition within sewerage collection systems so that they can make intelligent, informed decisions on the potential for sewer flushing systems in their community.

1.2 Report Format

The detailed findings derived from this study are presented in the two sections that follow which deal with development of the theoretical predictive model (Section 4); and the user's guidance procedures (Section 5). Section 4 is subdivided into five sub-sections: section 4.1 - the general methodology; section 4.2 - the conceptual model; section 4.3 - the design of the experiment; section 4.4 - the data preparation; and section 4.5 - the regression results.

1.3 Data and Information Sources

The data and information for this study were derived principally from four data sources: (1) the preliminary first phase field flushing results from Research Grant no. R804579 conducted by Northeastern University and Energy & Environmental Analysis, Inc., sponsored by U.S. EPA Storm and Combined Sewer Section; (2) sewer atlas physical data for portions of West Roxbury, Dedham, Newton and Brookline, Massachusetts for an infiltration/inflow study conducted by Energy & Environmental Analysis, Inc., for the Metropolitan District Commission; (3) sewer atlas physical data for portions of the City of Fitchburg, Massachusetts for a section of 208 combined sewer management study conducted by Energy & Environmental Analysis, Inc. for the Montachusetts Regional Planning Commission; and (4) sewer atlas physical data for portions of Dorchester and South Boston for a combined sewer management study sponsored by the Metropolitan District Commission.

SECTION 2

CONCLUSIONS

Conclusions derived from this investigation are as follows:

1. This present study develops a methodology for providing first-cut assessemnts of: a) the total amounts of solids and other pollution indicators, (lb/day), that deposit in a sewerage collection system; and b) the extent of the collection system over which the deposition takes place. A complex distributed-parameter dry weather sewage depostion model was first applied to 75 separate and combined sewer collection systems in eastern Massachusetts to generate estimates of solids deposited in the systems (lb/day). These estimated loads were then regressed with selected variables representing the physical characteristics of the collection system resulting in four predictive single term power functions with at most four independent variables. The regression analysis revealed a remarkable degree of fit of the nonlinear functions to the data set, with the R^2 values ranging from 0.85 to 0.95.

2. A comparative error analysis of predicted daily dry weather solids deposition for a test case collection system using the procedures generated in this study and the complex distributed-parameter model indicated a relative error ranging from 8 to 18 percent. The analysis also showed that the simplest of these procedures requiring comparatively little input data may be more cost effective than the more complex of these procedures for providing reliable "first-cut" estimates.

3. The complex distributed parameter model was tentatively calibrated using actual field flush information lending credulence to the adoption of the simplified procedures generated in this study.

4. The field analytical results of a sewer flushing project currently in progress were used to regress other pollutants such as BOD, COD, TKN, Total Phosphorous, NH_3 and VSS with suspended solids, all with high values of R^2, extending therefore the use of the predictive equations for total solids deposited to the estimation of other pollutants.

5. The effects of sewer system age and maintenance on solids deposition was simulated by considering prior sediment deposits to develop multiplicative coefficients to the four predictive equations for total solids deposited.

6. Extensive statistical analyses of sewerage system pipe slopes revealed that collection system pipe slopes can be represented by an exponential probability model. Analysis of the distribution of loads deposited versus cumulative pipe length lead to the development of generalized curves as a function of collection system mean slope for estimating the total fraction of collection system pipe footage over which a given percentage of the total loads deposit. These findings can be combined to locate segments associated with the required fractions.

SECTION 3

RECOMMENDATIONS

1. The major improvements to the methodology developed in this study involve extending the range of the regression model's applicability by expanding the observed ranges of the independent predictive variables used in the analysis. The reliability of the model's estimates will be improved. These improvements can be accomplished by augmenting the existing data base with new data from other sewer collection systems having different physical characteristics, in terms of average slopes, system configurations and extent, pipe sizes and shapes, etc., from those used in this study. Inclusion of systems with flatter and steeper average pipe slopes would broaden substantially the range of application of the regression equations derived in this study.

2. Another area meriting further study is the analysis of the cumulative distribution function of pipe slopes, especially for applications where only a limited amount of information on the collection system is available.

SECTION 4

DEVELOPMENT OF GENERALIZED PREDICTIVE MODELS

4.1 Overview

4.1.1 Objectives

The severity of combined sewer overflows is often associated with problems of dry weather solids deposition. Deposition build-up reduces conveyance capactiy and contributes to the pollutants that discharge into receiving waters. The analysis of remedial solutions to mitigate these problems involves estimating the amounts of solids deposited and their distribution throughout the system, so that control costs can be assessed.

The techniques presently available to estimate dry weather deposition in sewerage systems involve the use of computerized mathematical models, that are both complex and expensive and requiring more effort than appropriate for preliminary "first-cut", assessments. The objectives of this study is to develop predictive tools capable of defining on a preliminary basis:

a) the total amounts of solids and other pollutants that deposit in the sewerage system; and

b) the extent of the collection system over which the deposition takes place.

It is therefore possible with these two estimates to crudely evaluate the costs associated with sewer flushing and other means of reducing and/or eliminating these pollutants.

4.1.2 Executive Overview of Methodology

An empirical model relating pollutant deposition loadings to collection system characteristics is the goal of this study. The approach is to use least squares to fit parameters of a postulated model. The data base used in the fitting process consists, in part, of a number of collection system parameters developed from an extensive data analysis of the physical details of several major sewerage collection systems in eastern Massachusetts. These characteristics are some of the independent variables used in the analysis. The data for the dependent variables are the total daily sewage solids deposited in these collection systems for a wide variety of different operating conditions. These quantities are estimated using an existing exogenous model that uses extremely detailed information to compute deposition loadings throughout an entire collection system network. An analysis of the detailed outputs of this model together with some of the physical data of the collection systems provided the remaining independent variables in the data base. Simply stated, the dependent variable data was generated from an exogenous predictive analysis while the independent variable data was obtained from primary collection system data and from a secondary analysis of the exogenous simulation outputs with selected collection system data.

The results of the first phase field flushing program are described in Appendix A along with a brief overview of the entire project. The methodological details of the existing exogenous deposition model that predicts solids deposition in all segments of an entire sewerage collection system are presented in Appendix B. Preliminary calibration efforts using the data in Appendix A and the model in Appendix B are presented in Appendix C. These results are given to justify the application of that model to produce simulated data for the purposes of this study.

4.2 General Methodology-Detailed Overview

The general methodology used in the study is outlined in Figure 1. The first step is to define the general characteristics and parameters of the conceptual model. This discussion is presented in Section 4.2.1. Next, a series of experiments is designed to generate deposition loadings using the model described in Appendix B for a wide range of conditions likely to be encountered in practice. The regression equations would be valid for use over these ranges of conditions. The design of the experiments, described in Section 4.3, consists of defining the study areas to be used in the experiments and the hydraulic conditions under which the numerical experiments would be performed. The suspended solids per capita waste rate is discussed in the design of the experiments.

The next step involved the collection of all pertinent physical data associated with the selected collection systems, such as system configuration, pipe lengths, shapes and sizes, invert elevations, so that the deposition model referred to in Appendix B could be used. This physical data, together with the deposition model and the total loads deposited simulated for each of the collection systems. This work is described in Section 4.4.1

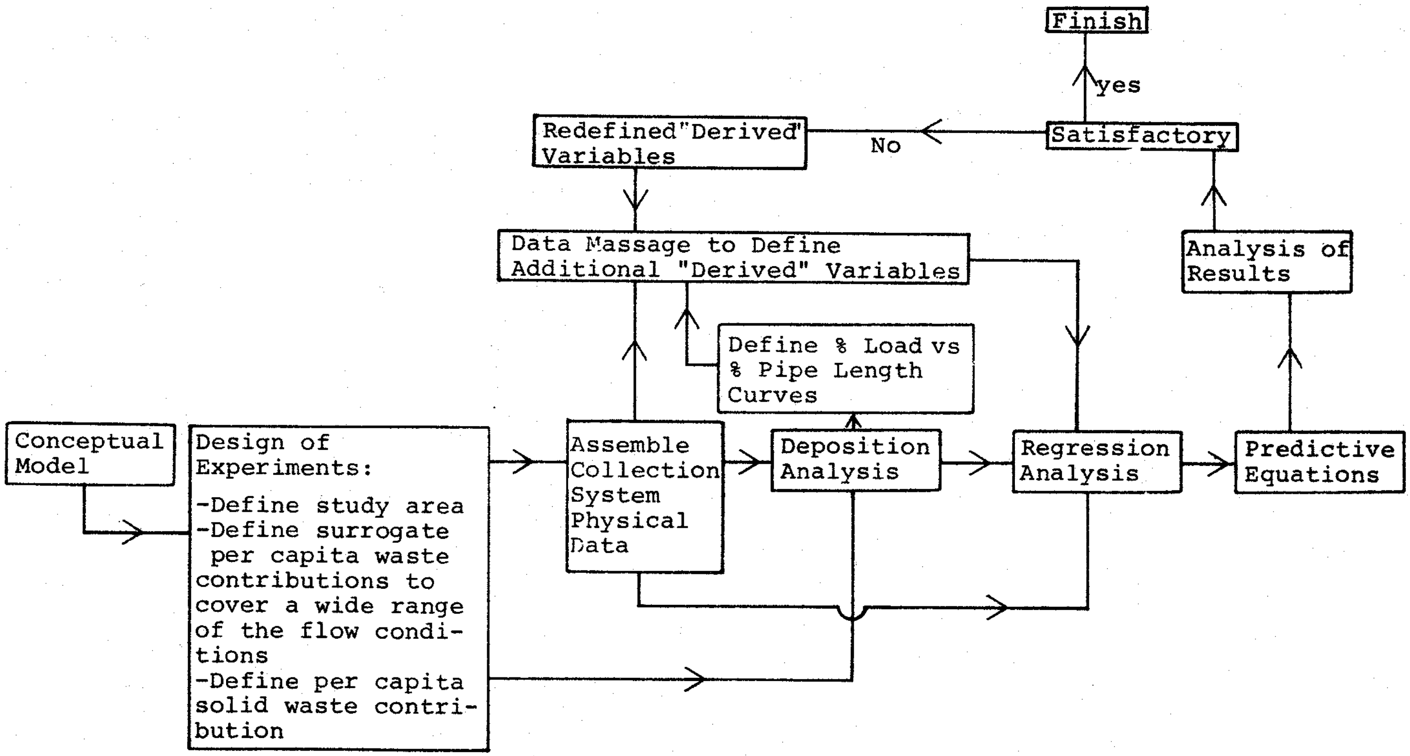

FIGURE 1. GENERAL METHODOLOGY OF THE STUDY

The analysis of the collection system service areas and total pipe lengths, distributions of pipe slopes and average collection system pipe diameters are presented in Section 4.4.2 and 4.4.4.

The deposition model results included the total lb/day deposited in each pipe segment of each basin and the total loads accumulated throughout each system. The information on loads by pipe segment is then used to generate curves for each basin, showing the accumulated percentages of the loads deposited against the accumulated percentage of pipe lengths where deposition took place. This part of the work is described in Section 4.4.5.

The physical data of the system together with the distribution of loads by pipe length are then used to define the derived variables L_{PD}, S_{PD} and $S_{PD/4}$ described in Section 4.4.6 to 4.4.8

The total loads by basin generated by the deposition model together with primary variables (pipe length, area, average slope, average diameter) and the derived variables (L_{PD}, S_{PD}, $S_{PD/4}$) are then used as input for the regression analysis described in Section 4.5.

Finally, the results of the regression analysis were examined and considered satisfactory and the process was complete.

4.2.1 Discussion of Model Variables

A discussion of the independent variables considered in the model and a few descriptive details of the preliminary analyses preceding the selection of the complete list of variables is given in this section.

The obvious and simplest of variables that can be used to characterize a collection system are the total service area, total pipe length, average slope and the average pipe diameter. It was believed from the onset of this study that these variables alone would not be adequate to explain the variability of the estimated loads from the deposition model. Clearly, a better characterization of the collection systems was necessary.

An exploratory analysis applying the deposition model on a number of sample collection systems revealed an interesting insight. Plots of the cumulative percentages of total loads deposited in each basin versus cumulative pipe lengths were prepared. A number of these curves can be inspected from Figures 12 and 13 on pages 36 and 37. The curves spread around the range of 70% to 90% of the total mass deposited suggested the use of the pipe length corresponding to 80% of the total mass deposited as a potential variable to include in the regression analysis.

Another set of plots of the cumulative distribution of pipe slopes for a few basins also suggested that the mean pipe slope alone would not be adequate to explain the effects of the pipe slopes on the variations of the deposition loads. A better characterization of the collection system pipe slopes could be obtained by defining various parameters at the flatter pipe slope range. Three other pipe slope parameters besides the mean pipe slope were initially selected for inclusion into the regression model. These parameters are as follows:

a) the pipe slope corresponding* to the percentage of the pipe length where 80% of the total load of the collection system deposits (S_{PD});

b) the average of the slopes in the basin below S_{PD} ($\bar{S}_{PD}$);

c) the slope corresponding to some fraction of S_{PD}, arbitraily taken as the slope corresponding to 1/4 the percentage of pipe lengths below which 80% of the total mass deposits ($S_{PD/4}$).

These slope parameters can be seen in Figure 2.

Further analyses revealed that $\bar{S}_{PD}$ and S_{PD} were very strongly correlated, so that retaining both in the regression analysis was not necessary. This finding was fortunate since the variable $\bar{S}_{PD}$ is much more difficult to determine than S_{PD}. The variable $\bar{S}_{PD}$ was excluded from the analysis.

Finally, it is clear that the deposition process is also strongly affected by the sewage flows in the system. Variations in population density and the degree of infiltration affects the dry weather flow rates. These effects were incorporated into the per capita waste rates used in the deposition model simulations and in the regression analysis. The summary list of variables considered in the regression analysis is the following:

1. Total collection system pipe length (L) - ft;

2. Service area of collection system (A) - acres;

3. Average collection system pipe slope ($\bar{S}$) - ft/ft;

4. Average collection system pipe diameter ($\bar{D}$) - inches;

5. Length of pipe corresponding to 80% of the solids deposited in the system (L_{PD}) - ft;

* Note that the correspondence indicated in Figure 2 does not necessarily imply that the pipe length over which 80% of the load deposits has slope smaller than or equal to S_{PD} at all segments. See section 5.3.2

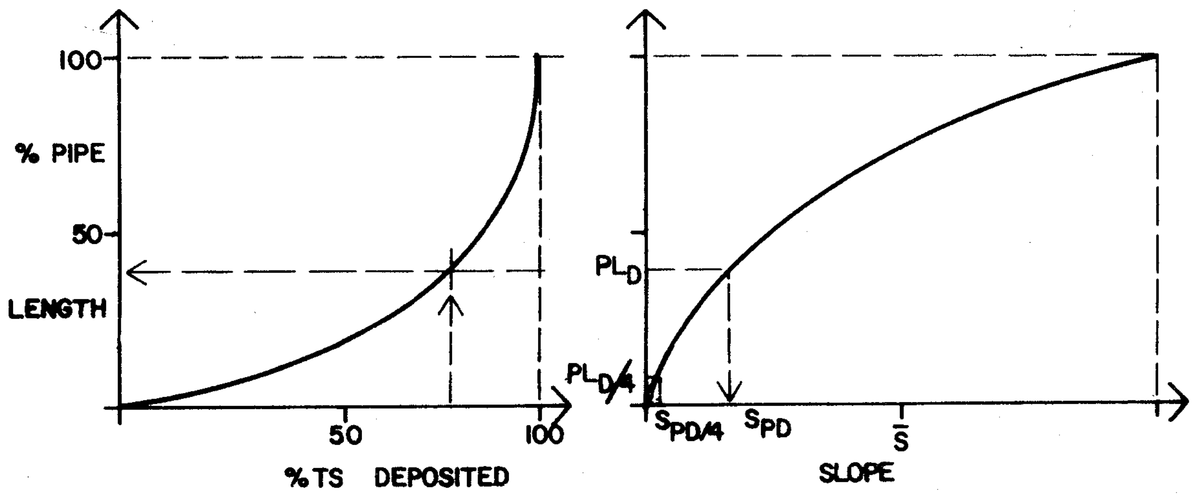

FIGURE 2. COLLECTION SYSTEM PIPE SLOPE VARIABLES

6. Slope corresponding to $L_{PD}(S_{PD})$ - ft/ft;

7. Slope corresponding to 1/4 of the percentage of pipe length (PL_D) below which 80% of the solids deposit ($S_{PD}/4$) - ft/ft; and

8. Flow rate per capita, including allowance for infiltration (q) - gpcd.

With respect to the mathematical forms of the regression model both linear and alternative non-linear models were initially postulated. Non-linear fitting techniques were not needed in the analysis since the linear models, that is, the strictly additive form and the logarithmic multiplicative form converted in the log domain, resulted in excellent fitting results with the R^2 approaching 95%.

4.3 Design of Experiment

In this section an overview will be presented of how collection system data from three major sewerage sytems was used to design the data base for the multivariate regression experiment. A description of the three sewer systems whose data were assumed to represent an adequate sample from the universe of all collection system is presented in section 4.3.1. A discussion of the per capita waste rates used in the experiment is presented in section 4.3.2. These surrogate waste rates reflect wide variations in population density and infiltration conditions encountered in practice. This parameter can be considered as a decision variable from a planning standpoint. Various sewer system age and maintenance considerations are discussed in section 4.3.3.

4.3.1 Description of Three Sewer Systems

The physical characteristics of the three major collection systems used in this analysis derive from three prior studies. The first area, covering portions of West Roxbury in Boston, Dedham, Newton and Brookline is strictly separated. The second area covering major portions of Dorchester and South Boston, two neighborhoods of the Boston metropolitan area is a mixed combined and separate area while the third basin covering a portion of the City of Fitchburg is served by a combined sewer system. The total pipe length, service area and pipe density for each basin are given in Table 1. The total pipe footage for all three areas entails 196 miles of separate and combined sewer systems encompassing a total area of 8.9 square miles.

TABLE 1. SEWER DENSITY (mi/acre)

Overall System	Pipe Length (mi)	Area (acres)	Pipe Density (mi/acre)*
WRNDB** 35 basins	64.87	2464.	0.026
Dorchester (37 basins)	119.85	2753.	0.044
Fitchburg (3 basins)	11.17	485.	0.023

* Weighted averages: by pipe length: 0.036, by area: 0.034.
** Sewerage system with area covering portions of West Roxbury, Dedham, Newton and Brookline in Boston metropolitan area.

The land use in the first area in West Roxbury and neighboring communities is mostly moderate to high density single and two family dwellings with a population density ranging from 10 to 15 people/acre. The topography is mild with several hilly portions in the area. This area was investigated in a recent infiltration/inflow study and was subdivided into 35 distinct sewer collection subsystems.

The land use in Dorchester and South Boston is mostly high density multi-family dwellings with population density ranging from 30 to 60 people/acre. The topography in Dorchester is moderate with a number of hilly sections while portions of South Boston are fairly flat. There are a total of 37 distinct sewer collection systems in this study area.

The land use in the third area in Fitchburg is mixed commercial and high density multi-family dwellings with a small portion of single family homes. The population density is similar to Dorchester. The study area is subdivided into three collection systems.

A total of 75 different sewer collection systems form the data basis for the analysis. It is assumed that these basins collectively represent a wide variety of different pipe slope conditions, pipe sizes and shapes and network system configurations. Some basins serve narrow strips of land while others are broad fanned-shape with a high hierarchial network order. A central assumption is that the collection system characteristics represented by the sample of 75 sewer sheds is an adequate representation of the total universe of collection systems. This assumption is not completely valid since, for example, extremely flat collection systems were not part of the sample set. Future work should broaden this data base. This sample however is deemed reasonably complete for the purposes of this analysis.

A complete sewer atlas of manhole to manhole descriptive physical data including pipe length, slope, shape, size and network ordering designations was available for each of these systems. Much of this data had been previously processed for computer application although a considerable portion of the data had to be placed in EDP format for purpose of this study. Roughly 6000 manhole to manhole segments incorporating all of the aforementioned parameters were necessary to represent the hydraulic characterization of the 75 sewer collection systems.

4.3.2 Range of Flows

The degree of deposition in a sewer pipe is strongly dependent on the discharge. As flow increases through a pipe the depth, velocity, hydraulic radius all change resulting in higher shear stress with less deposition. Discharge therefore is an extremely imporant parameter in the analysis. The dry weather discharge in a sewer system is dependent upon the local population density, the domestic per capita contribution, the degree of infiltration and any industrial waste contributions.

It was envisioned that a single per capital surrogate waste rate would be generated incorporating a wide range of population density and infiltration conditions encountered in practice.* This variable would embed all these variations and be used in both the deposition model to predict daily dry weather solids deposition and in the regression model as an independent variable.

Population densities ranging from 15 people/acre up to 90 people/acre were considered. Using a factor of 0.035 miles of sewer per acre the corresponding number of people per 100 feet of sewer pipe was computed. These factors are shown in Table 2 and are used in the deposition model which requires as input the number of people per 100 feet of sewer.

The dry weather per capita contribution of 85 gpcd was considered fixed in this analysis. Four different infiltration estimates of 500, 1000, 2000 and 4000 gallons per acre per day were used to cover the range of normally encountered infiltration conditions. The adjusted per capita waste rates incorporating the various rates of infiltration for the range of population densites considered in the analysis are shown in Table 3. These per capita values are again adjusted to the mid-range of population density of 45 people/acre and are given in Table 4. This last conversion permits considering one single range of surrogate per capita flow rates using 45 people/acre as the norm. Four different flow rates are considered in the analysis and cover the full range of per capita waste rates for different population densities and infiltration conditions. The per capita waste rate used in the analysis are: 40 gpcd, 110 gpcd, 190 gpcd and 260 gpcd.

The per capita solids waste rate of 0.5 lb/capita/day was used in all computations. This parameter was established from field measurements in the sewer flushing project described in Appendix C. All regression results presented in Section 4.5 can be linearly scaled for any other desired per capita solids waste rate.

4.3.3 Age and Maintenance Conditions

The presence of long-term accumulations of organic matter, sand, gravel, grit and debris in the form of sediment beds,

* Industrial waste contributions were not explicitly considered. The user can readjust the per capita waste rates used in this analysis to reflect industrial contributions.

TABLE 2. POPULATION DENSITY (PERSONS/100 FT OF PIPE)

Density (person/acre)	Persons/100 ft of pipe*
15	8.15
30	16.30
45	24.46
60	32.61
90	48.91

* Assumes 0.035 mi/acre or 184.8 ft of pipe/acre

TABLE 3. PER CAPITA WASTE RATES FOR VARIOUS POPULATION DENSITIES AND INFILTRATION RATES*

Density	Infiltration Rate (gpad)**			
(person/acre)	500	1000	2000	4000
15	118.3	151.7	218.3	351.6
30	101.7	118.3	151.7	218.3
45	96.1	107.2	129.4	173.9
60	93.3	101.7	118.3	151.7
90	90.6	96.1	107.2	129.4

* Assumes a dry weather contribution of 85 gpcd

** gallons per acre per day

TABLE 4. PER CAPITA VALUES RELATIVE TO THE DENSITY OF 45 PERSONS/ACRE

Density	Infiltration Rate (gpad)			
(person/acre)	500	1000	2000	4000
15	39.09*	50.14	72.14	116.20
30	67.28	78.20	100.27	144.29
45	96.10	107.20	129.40	173.90
60	124.39	135.59	157.72	202.25
90	179.69	190.60	212.62	256.25**

* minimum value

** maximum value

shoals, or bars can significantly alter the hydraulic characteristics and accordingly the degree of deposition, particularly for lateral pipes with little dry weather discharge. These accumulations can easily result in new well-constructed sewer systems with sound joints and few hydraulic obstructions such as protruding house connections,etc. Similar deposits can occur in systems that are rodded and frequently cleaned but either are old and/or have poor joints and many hydraulic obstructions. Perforated manhole lids provide the perfect opportunity for children to jam sticks into manholes that can result in massive blockages of accumulated rags and toilet paper. The above conditions are but a few of the possible age and maintenance problems encountered in practice.

Three different categories of sewer system age and maintenance were considered in this analysis. The first category of clean pipe conditions represents good maintenance practices and well-constructed sewer systems. No sediment beds were considered in this case.

Two cases simulating different degrees of maintenance other than perfect clean pipe conditions were also considered. In the first case or the intermediate maintenance category, sediment beds ranging from 1 to 3 inches in depth were assumed for all pipes with slopes less than 0.0075. Figure 3 shows the assumed ranges of beds between pipe slopes of 0.0005 and 0.0075. In the third category, the zero maintenance care, the sediment beds range from 3 to 6 inches for the same range of pipe slopes. This range was established using judgment and also based on visual inspection of numerous combined sewer pipes in eastern Massachusetts combined sewer systems.

These three conditions were used in the deposition model analysis to compute daily collection system deposition loadings.

4.4. Data Preparation for the Regression Model

4.4.1 Deposition Model Results

4.4.1.1 Brief Description of the Deposition Model

The deposition model used in this study to generate estimates of solids deposition in the sewerage systems selected in Section 4.3 is described in detail in Appendix B. The model considers peak daily dry weather flow and uses a shear stress critera to determine the limiting diameter of the solid particles that deposit at each segment. Then, with this limiting particle size and assuming a given distribution for the particle sizes present in the dry weather sanitary flow, the model determines the percentage of the suspended solids that deposit at each pipe segment. The model also has mechanisms to account for the fact that particles of diameters up to a given size that deposit in a given pipe segment are not available for deposition in downstream segments.

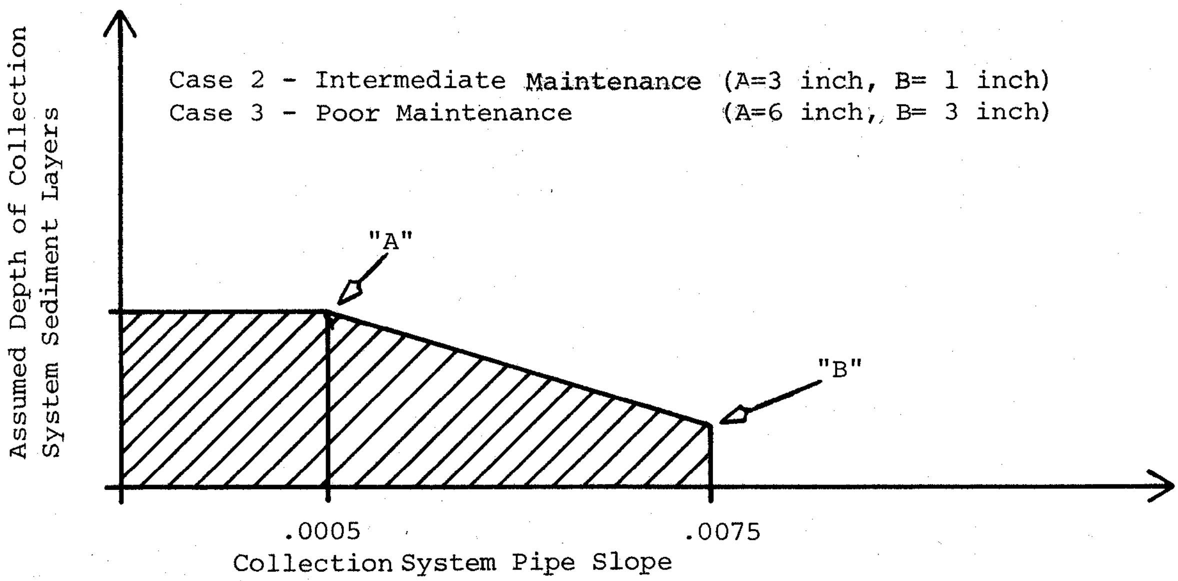

FIGURE 3. REPRESENTATION OF SEDIMENT BEDS AND PIPE SLOPE FOR TWO AGE AND MAINTENANCE CONDITIONS

Some of the results given by the model are: (1) the flow conditions at each pipe segment, including discharge, average velocity, water depth and shear stress; (2) the loads (lb/day) deposited at each pipe segment and (3) the accumulated value of the loads deposited in all upstream segments. A verification of the results given by the deposition model is presented in Appendix C.

4.4.1.2 Input Data Required by the Deposition Model

The input data required by the deposition model consists of:

- Segment identification (by a segment number);
- Segment upstream and downstream pipe inverts;
- Segment length;
- Pipe shape (10 shapes possible);
- Pipe sizes (diameter or height and width);
- Segment type (zero, one or two tributary segments);
- Network location designation (defined by the segment type in conjunction with the next downstream segment number);
- Sediment depth in the segment;
- Population per 100 feet of pipe;
- Average daily waste flow contribution in gpcd;
- Peak daily to average flow peaking coefficients (see page B-3);
- Manning's resistance coefficient, n, and its variability with flow depth; and
- Total solids contribution in lb/capita/day.

4.4.1.3 Deposition Input Data Preparation

In Section 4.3, the description of the three different sewerage systems considered in this study was presented. A total of 75 subsystems were used in this analysis including 35 separate collection systems from the WRNDB sewer system, 37 collection systems from the Dorchester and South Boston combined sewer systems; and 3 collection systems from the Fitchburg combined sewer system.

All the necessary physical data in the form of computer cards were available for the Dorchester and Fitchburg system from previous studies. For the WRNDB system all the pipe elevations, lengths, shapes and sizes were also available from a previous study, but all the segment numbering and the additional information required to establish the system configuration had to be generated in this study.

Other information on waste flow rates and solid matter contribution to the systems, necessary to run the model, were given in Section 4.3.

4.4.1.4 Deposition Model Runs and Results

Three sets of runs were performed for all 75 basins. The first set of runs were performed assuming no previous sediment deposits present in the pipes, that is clean pipe conditions. The second set of runs were performed in which sediment depths ranging from 1 to 3 inches were assumed to represent moderate maintenance conditions. The third set of runs were performed assuming sediment depths from 3 to 6 inches intended to simulate poor maintenance.

Selected information from these runs were punched out on cards for use in future phases of the study. The values of the loads (lb/day) deposited by pipe segment were used to define for each basin the accumulated percentages of the total load versus the accumulated percentages of total pipe lengths where deposition occurs. An overall curve for all 75 basins was also prepared. These curves were useful in deriving several variables used in the regression analysis. The total loads per basin were used as the observed values ofthe dependent variable in the regression analysis.

4.4.2 Areas and Total Pipe Lengths

The total service area and total pipe lengths were known from prior studies for all 75 basins. These values were necessary for the regression analysis described in Section 4.5, and are presented in Table 5. The first 35 basins cover portions of the WRNDB sewerage system. Basins 36 through 72 cover the Dorchester and South Boston sewerage system while the last three basins cover portions of the City of Fitchburg sewerage system. The data on Table 5 was also used for a simple regression of total pipe length on total area and is described in Section 5.2.2. This regression may be useful in extreme cases where the total pipe length is not known or cannot be immediately determined.

4.4.3 Distribution of Pipe Slopes

The regression model proposed in Section 4.2.1 included several collection system pipe slope parameters, S_{PD} and $S_{PD/4}$, that required computation of the cumulative pipe slope distributions. A computer program was prepared to compute these distributions from data on the pipe segments upstream and downstream invert elevations and segment lengths. The program computed the slope distribution weighing the segment slopes by their lengths. The mean, standard deviation, coefficient of variation, coefficient of skewness and coefficient of kurtosis of pipe slopes per collection system were also computed. The program computed the distribution and the aforementioned statistics for each system (WRNDB, Dorchester and Fitchburg) and finally an

TABLE 5. - TOTAL PIPE LENGTHS AND AREAS OF THE BASINS

BASIN NO	PIPE LENGTH (FT)	AREA (ACRE)
1	47180.	230.
2	5945.	38.
3	610.	5.
4	669.	7.
5	3309.	19.
6	360.	5.
7	1900.	9.
8	2251.	13.
9	650.	3.
10	1160.	8.
11	2158.	6.
12	1410.	13.
13	15610.	84.
14	1551.	70.
15	990.	70.
16	1305.	6.
17	71621.	641.
18	3279.	58.
19	14415.	100.
20	263.	6.
21	489.	8.
22	1146.	4.
23	4180.	6.
24	27385.	173.
25	12653.	90.
26	3331.	19.
27	14016.	82.
28	738.	6.
29	14997.	120.
30	14540.	140.
31	1374.	6.
32	16988.	96.
33	17131.	100.
34	7728.	45.
35	26981.	178.
36	6245.	42.
37	7735.	33.
38	1750.	29.
39	4265.	19.
40	3485.	17.
41	3400.	26.
42	3170.	16.
43	4000.	25.
44	5060.	25.
45	11325.	52.
46	13133.	44.
47	7757.	24.
48	7764.	42.
49	112638.	245.
50	875.	5.
51	5200.	36.
52	4501.	27.
53	11890.	51.
54	5830.	28.
55	2235.	15.
56	7145.	34.
57	5276.	91.
58	3115.	9.
59	10585.	120.
60	8741.	65.
61	35501.	228.
62	13051.	78.
63	5635.	26.
64	11325.	54.
65	33005.	177.
66	9899.	47.
67	5644.	30.
68	14220.	57.
69	4492.	24.
70	35033.	233.
71	134528.	315.
72	69274.	360.
73	31748.	264.
74	12092.	78.
75	14754.	143.

overall distribution and the first four moments of all data lumped into one data set.

Plots of the slope distributions for a few basins are shown in Figures 4 and 5. The concave shapes of those cumulative distributions (CDF) without a point of inflexion, suggest an exponential distribution for the pipe slopes. Several of the cumulative distributions were plotted on normal, log normal and Gumbel's probability paper. All plotted curves resulted in very non-linear shapes, indicating that the pipe slopes do not follow any of those distributions. Plots of the complementary CDF of the pipe slopes on semi-logarithmic paper, nontheless, resulted in remarkably linear shapes shown in the illustrative cases in Figures 6 through 10. Although no formal numerical test of goodness-of-fit was performed, this fact indicates that, at least for the sample data used in this study, the distribution of the pipe slopes is exponential.

The solid lines drawn on Figures 6 through 10 were plotted using the expression of the exponential cumulative distribution function given by:

$$F_S = 1 - e^{-s/\bar{S}} \qquad (1)$$

where $F_S = P(s \leqslant \bar{S})$ (cumulative pipe slope distribution);

s = any given slope;

$\bar{S}$ = the mean slope computed for the basin, as indicated above; and

e = the base of the natural logarithms.

Figure 11 presents the histograms for the WRNDB, Dorchester and Fitchburg sewerage systems and the overall histograms considering all data. The slope values corresponding to the intervals in Figure 11 are given in Table 6.

Two observations can be noted from these histograms:

a) the shapes of the histograms for all 13 systems are similar with minor differences between them (the same is true for the global histogram compared to any of the other three); and

b) they all indicate an exponentially decaying shape, characteristics of the exponential distribution with the CDF given by equation (1).

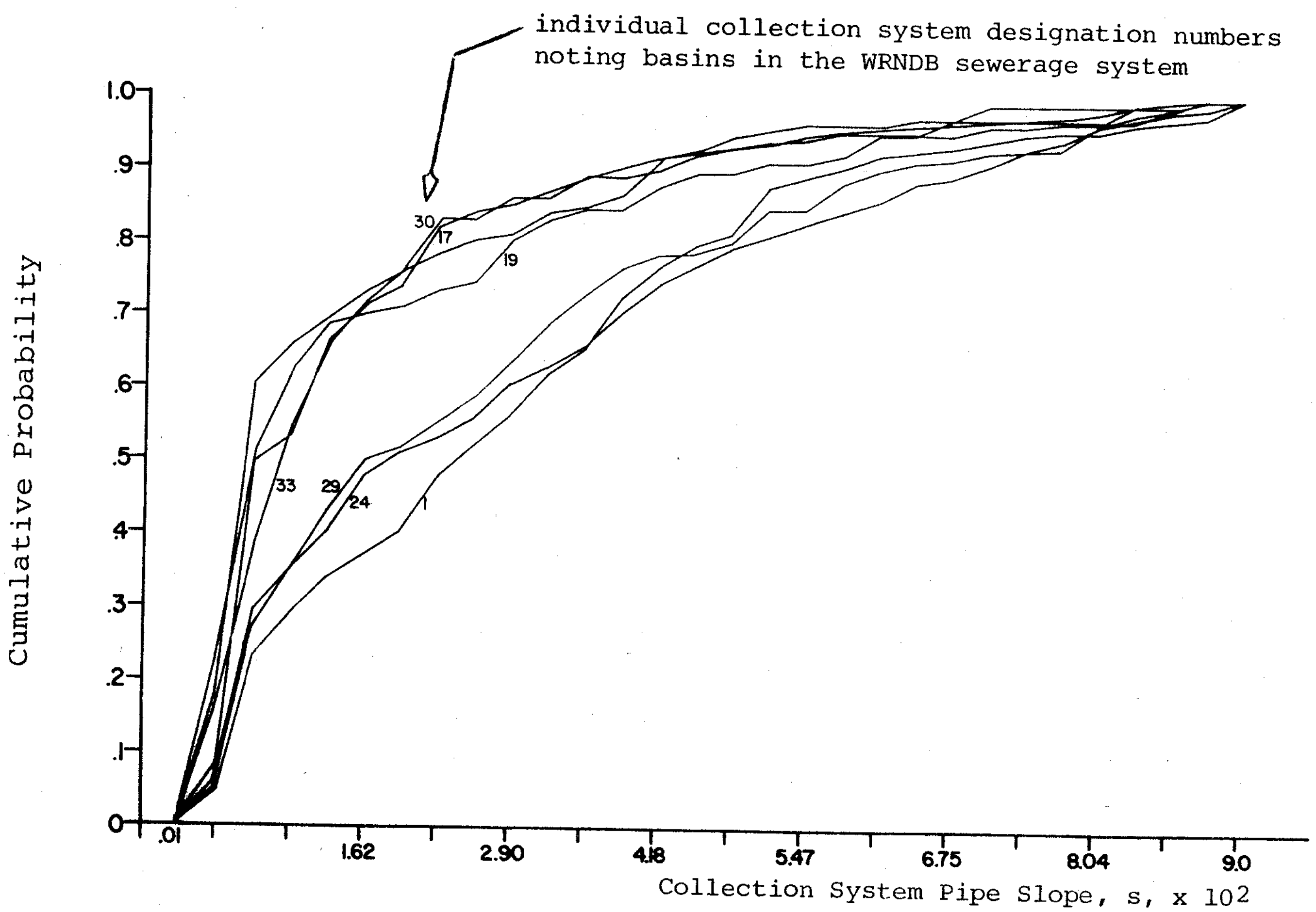

FIGURE 4. CUMULATIVE DISTRIBUTION OF PIPE SLOPES PER COLLECTION SYSTEM

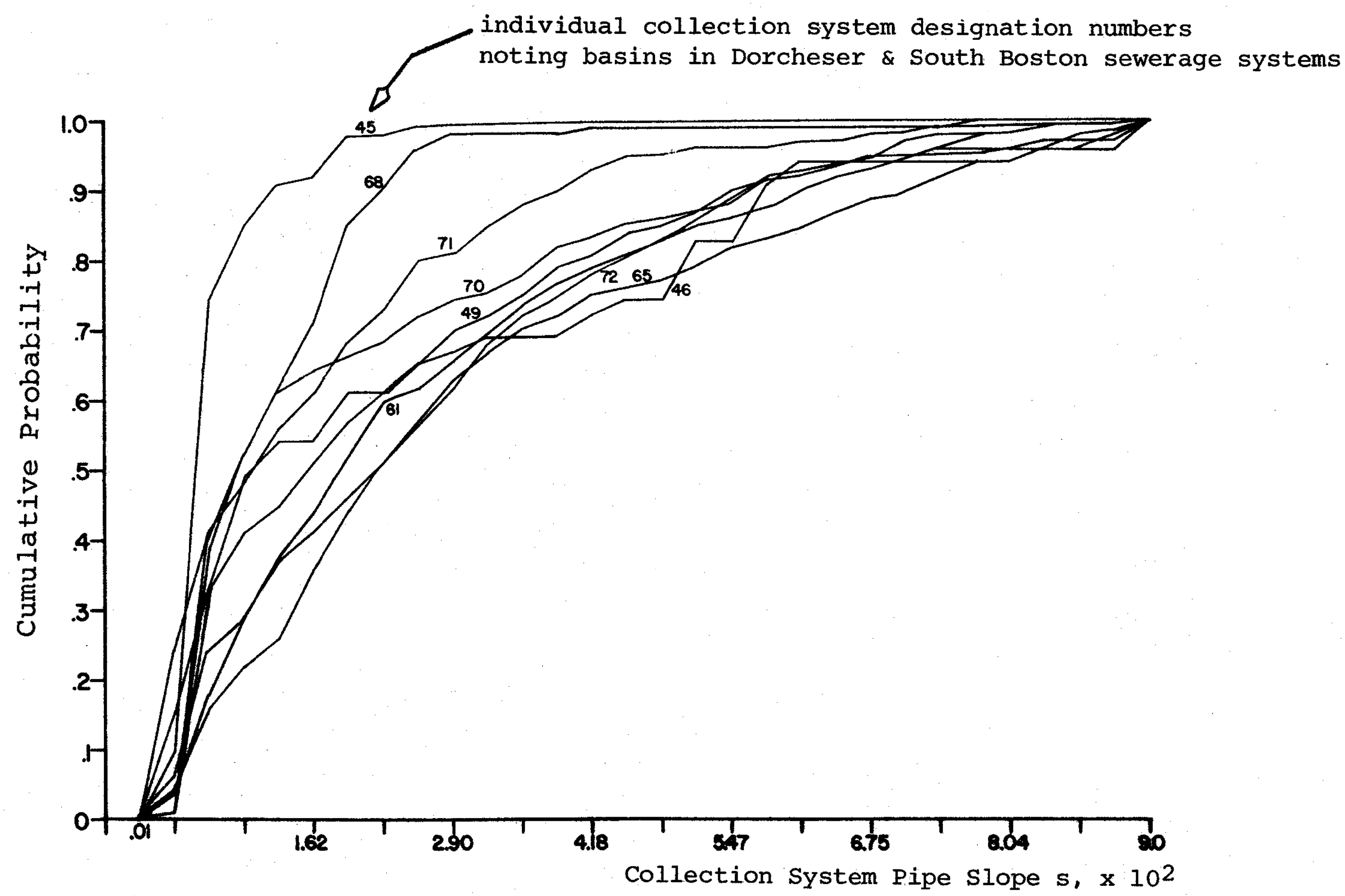

FIGURE 5. CUMULATIVE DISTRIBUTION OF PIPE SLOPES PER COLLECTION SYSTEM

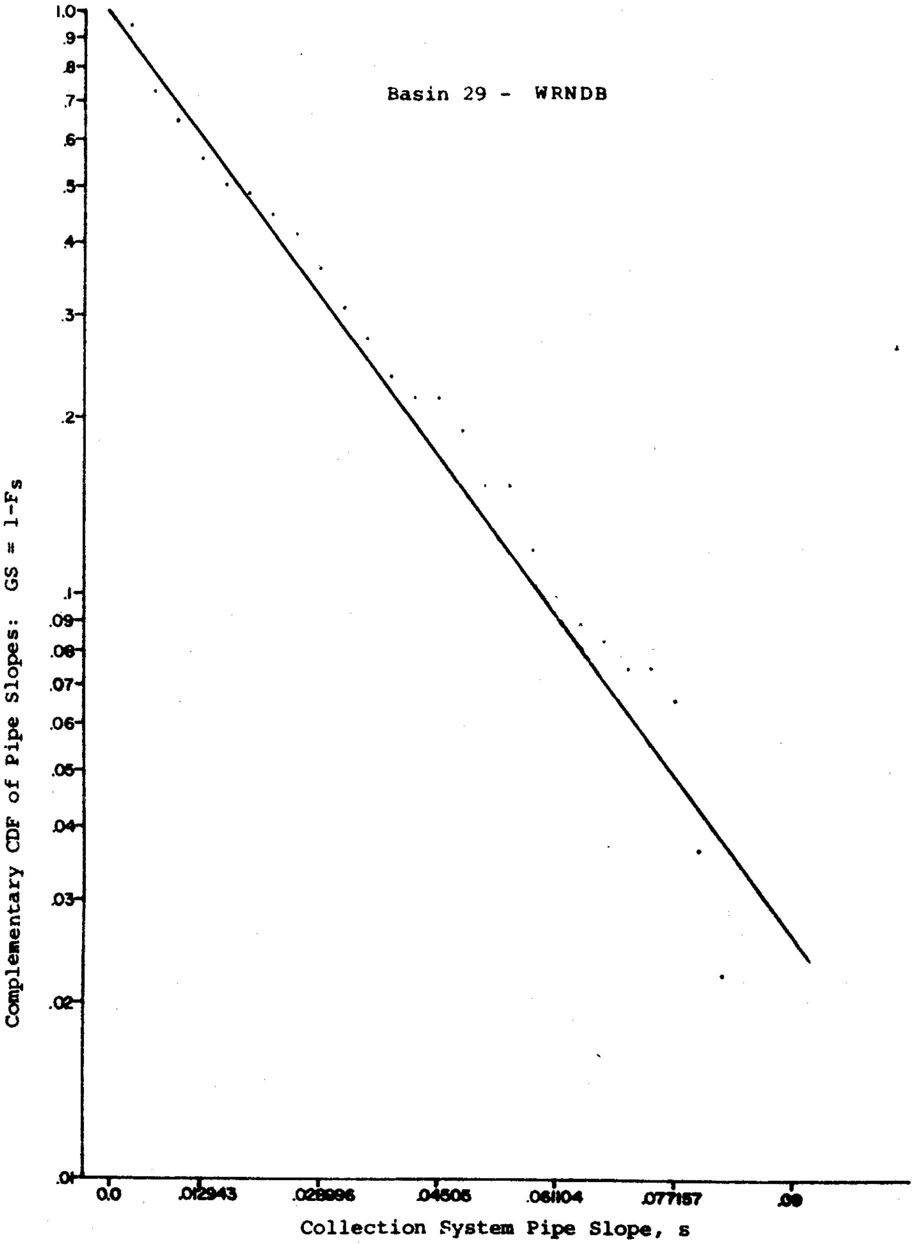

FIGURE 6. COMPLEMENTARY DISTRIBUTION OF PIPE SLOPES: $G_s = 1-F_s$

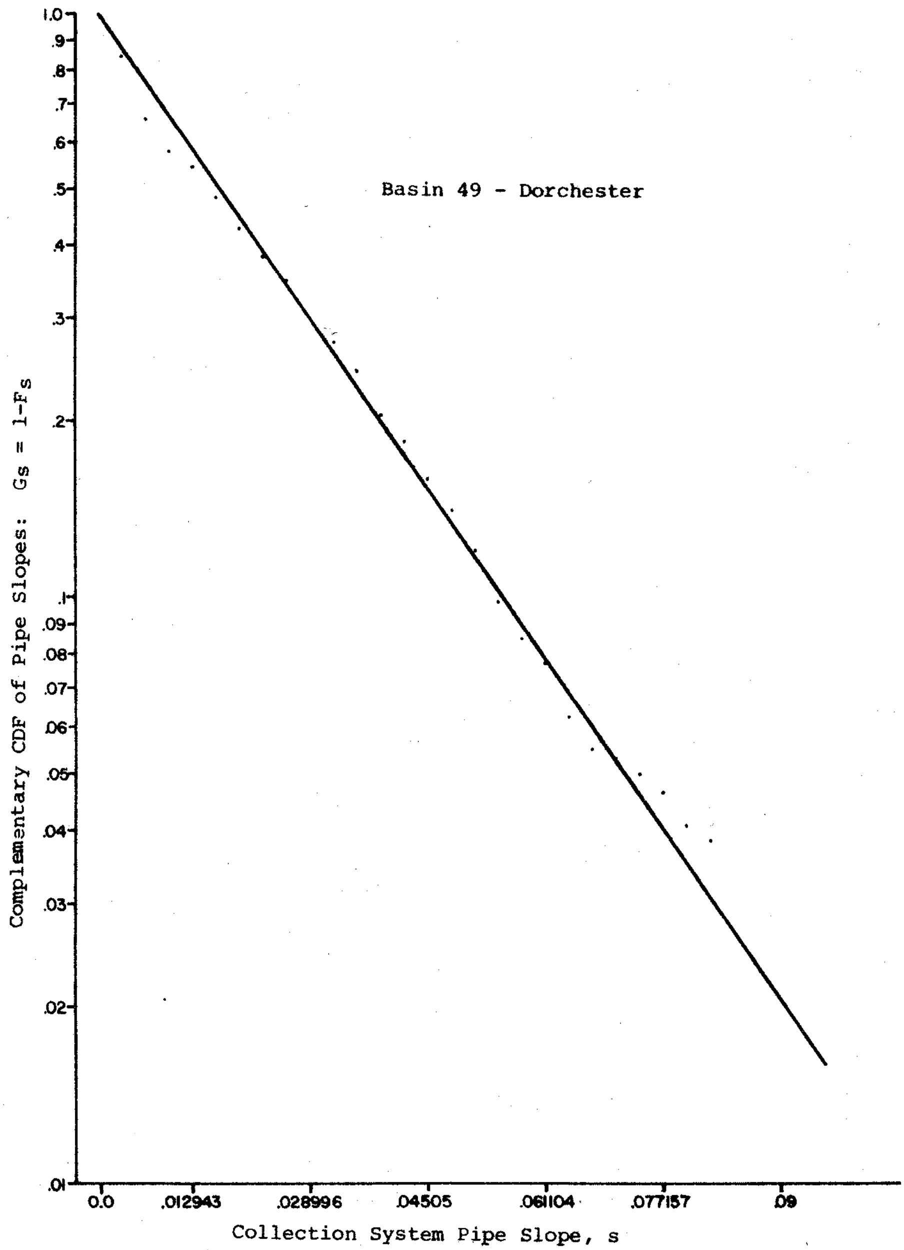

FIGURE 7. COMPLEMENTARY DISTRIBUTION OF PIPE SLOPES: $G_s = 1-F_s$

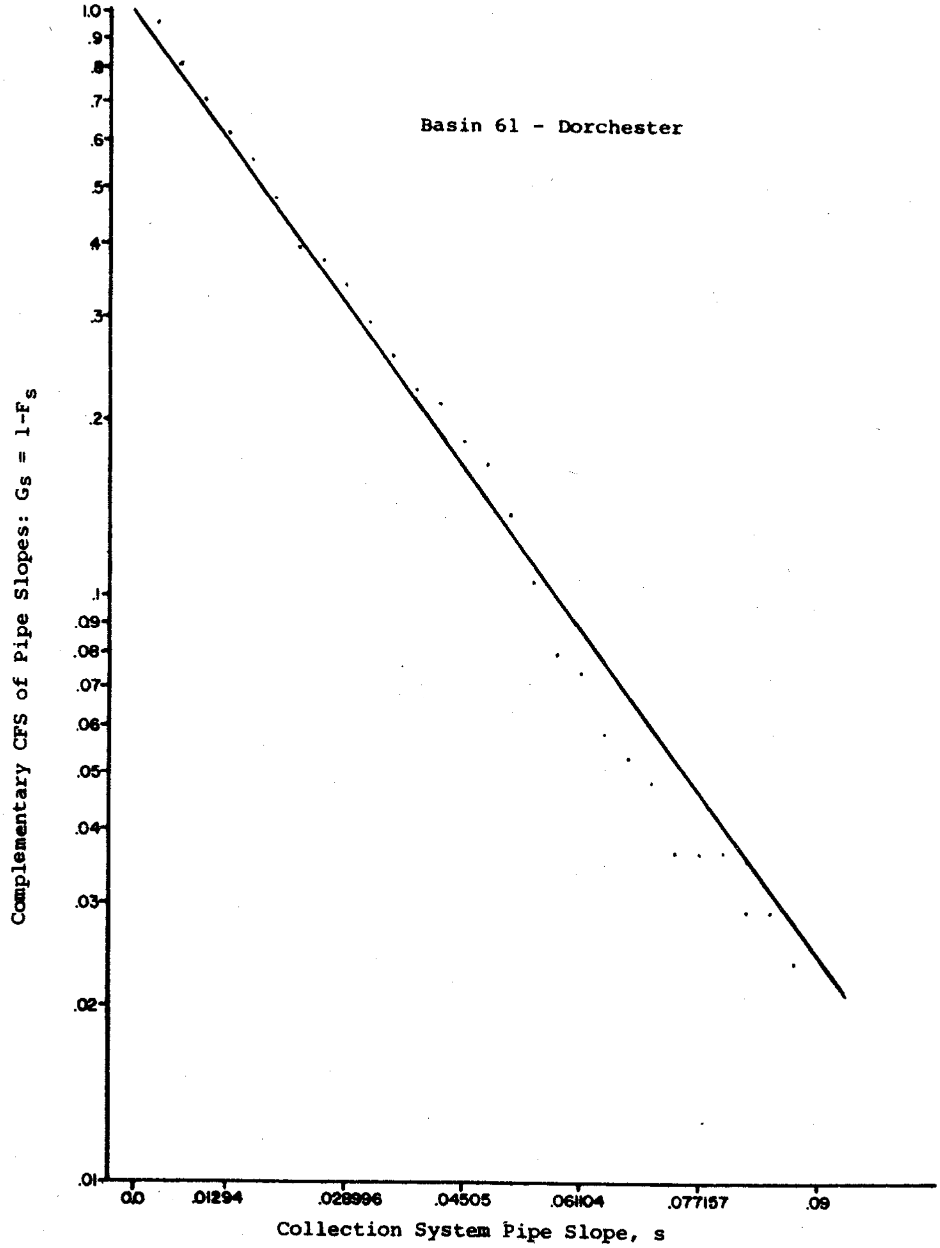

FIGURE 8 . COMPLEMENTARY DISTRIBUTION OF PIPE SLOPES: $G_s = 1-F_s$

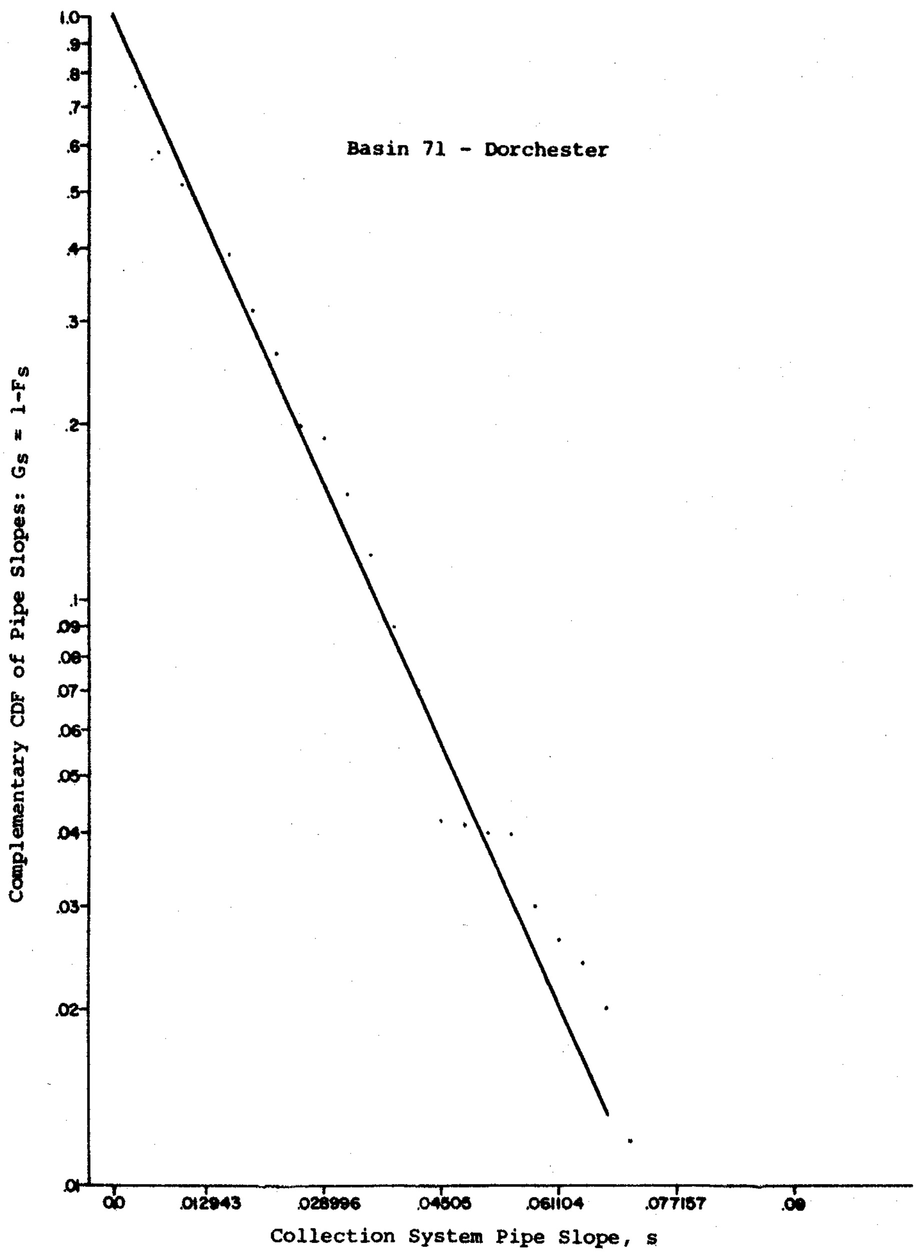

FIGURE 9. COMPLEMENTARY DISTRIBUTION OF PIPE SLOPES: $GS = 1-F_S$

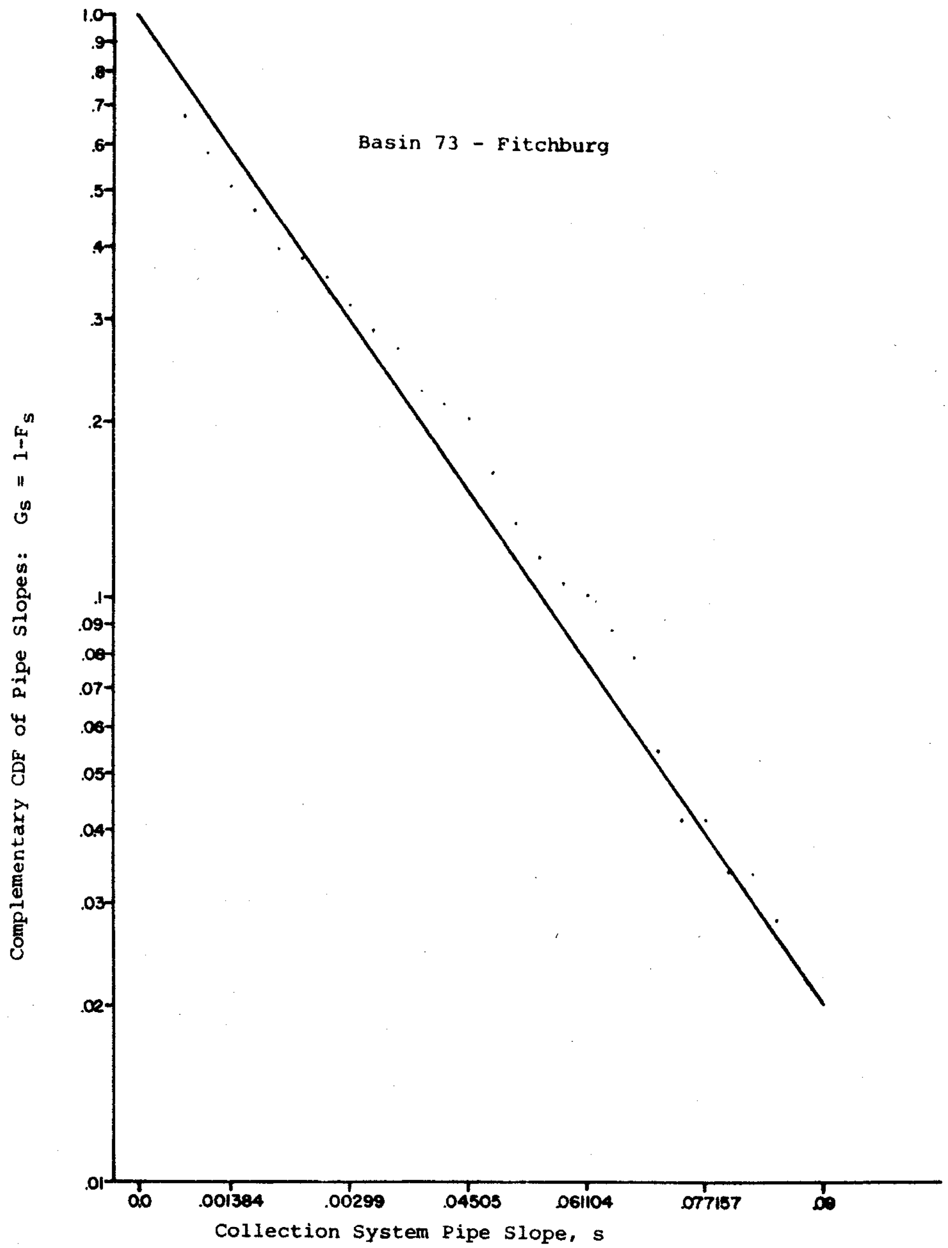

FIGURE 10. COMPLEMENTARY DISTRIBUTION OF PIPE SLOPES: $G_s = 1-F_s$

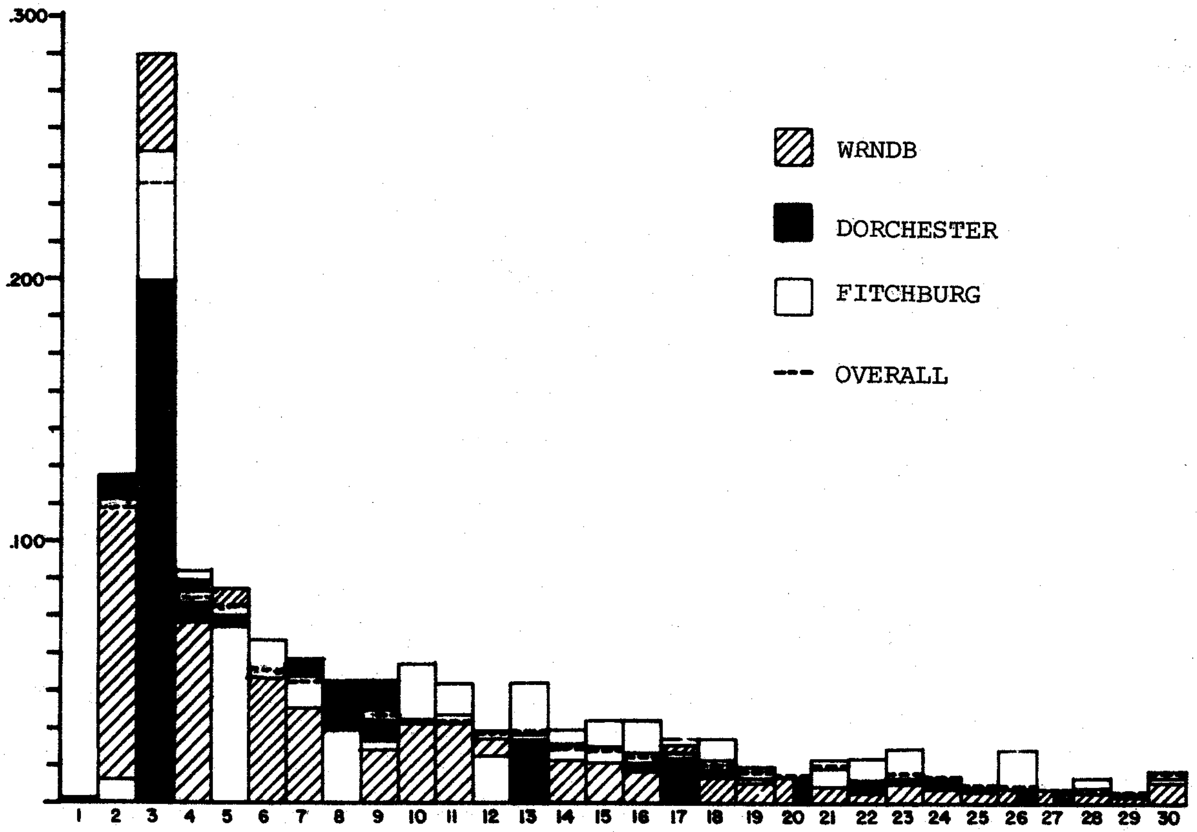

FIGURE 11. HISTOGRAMS OF COLLECTION SYSTEM PIPE SLOPES